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HYDRAULIC HETEROGENEITY IN A HIGHLY WEATHERED BASALTIC REGOLITH: IMPACT ON LATERAL-FLOW AND SOLUTE TRANSPORT

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Reliable on-ground information on groundwater (GW) hydraulic heterogeneity is required to determine flow direction and quantities, but its experimental characterization is difficult because of the complexities associated with the interaction involving the temporal changes in space modified by regolith stratigraphy. The impact of the aforementioned variables, particularly stratigraphy in a 51 m thick highly weathered basaltic regolith in the northeast humid tropics of Queensland, Australia, on flow gradients and directions was investigated in this study. Regolith cores at 1 m increments indicated that there were 3 different major strata. The temporal changes in water table, hydraulic- and pressure- heads, and solute concentrations in space indicated the top 51 m aquifer was contiguous, dynamic and hydraulically differentiated into three segments which approximately corresponded with the regolith strata. The lateral-flow and solute transport from each aquifer segment was controlled by depth to water table, the number of regolith layers the segment covered, and the solute concentration.

INTRODUCTION

The groundwater (GW) hydraulic pressure and elevation heads, and regolith saturation status have been usually considered as the primary variables that controlled the occurrence, nature, and the rate of fluid movement in regoliths, and the active flow systems were usually shallow (Boutt et al. 2010). Love et al. (1993) reported the major proportion of the regional flow from the Gambier Embayment aquifer in South Australia was from the upper segment of an unconfined aquifer and the flow was controlled primarily by ground elevation. Experimental characterization of the hydraulic heterogeneity is expensive and difficult, if not impossible (Johnson, 2008; Harte, 1997; Conger 1996; Keys, 1988; Keys and MacCary, 1971). For water resource assessment and GW hydraulic investigations several workers have used geophysical (Conger, 1996; Keys 1988; Keys and MacCary, 1971) to characterize hydraulic heterogeneity while others have used lithologic log data (Johnson, 2008; Harte 1997). However, there had been limited attempts to explore the feasibility and applicability of geophysical and lithologic approaches to characterize GW lateral-flow and solute transport from highly weathered regolith.

Solute lateral transport information is essential in situations where the lateral-flow contributes substantially towards the total annual or seasonal flow, particularly for intensively cultivated agricultural catchments and more specifically for the northeast humid tropics of Queensland, Australia. Such catchments had been implicated in the loading, via runoff, of soluble forms of N and P into surface waters and consequently on ecosystem health issues (UNEP, 1989; Larkum and Steven, 1994; Carpenter et al. 1998; Baker, 2003; Selman and Greenhalgh, 2007). In Queensland northeast humid tropics of Australia the export of N and P estimates from non-point sources has based primarily on runoff from agricultural catchments (Baker, 2003). Even though ˜ 60% of the annual flow in perennial streams that discharge into the UN listed World Heritage Great Barrier Reef (GBR) is sourced from GW (Cook et al. 2001) the exports associated with base flow discharges has not been well documented despite the fact that large quantities of soluble forms of N and P were found in shallow GW (Rasiah et al. 2003; 2010; 2011a, b). The primary reason for this being is the unavailability of sufficient information in aquifer and regolith characteristics that control and determine lateral-flow discharges. Thus, in this study the impact of regolith stratigraphy of a 51 m thick highly weathered basaltic regolith in the northeast humid tropics of Queensland, Australia, on temporally varying flow gradients and directions in space was investigated.

MATERIALS AND METHODS

Study area

The study was conducted in the humid tropical Johnstone River Catchment in northeast Queensland, Australia. The catchment is about 1634 km^2 in area and is located at 17^o 30' S and 145^o 50' E (Figure 1a). Pristine rainforest covers about 50-51% of the mountains and hills of the catchment, pasture 28% (both dairy and beef) at midslopes, 12% sugarcane, and 8% banana at the lower aspects of landscape (Prove and Moody, 1997). The major rivers in the catchment are the North and South Johnstone Rivers. Both rivers rise in the southeastern section of the Atherton Tableland (Malanda elevation 740 m), pass through large areas of rainforest in the midsection of the catchment and drain the undulating lowlands and floodplains of the lower catchment. The rivers converge at Innisfail to become the Johnstone River estuary which discharges into the GBR.

Regolith Characteristics

Sections of regolith in the catchment are highly weathered, stratified, basaltic and alluvial material, and can range in thickness from 50 to 120 m (Hair, 1990; Isbell 1994). The stratification

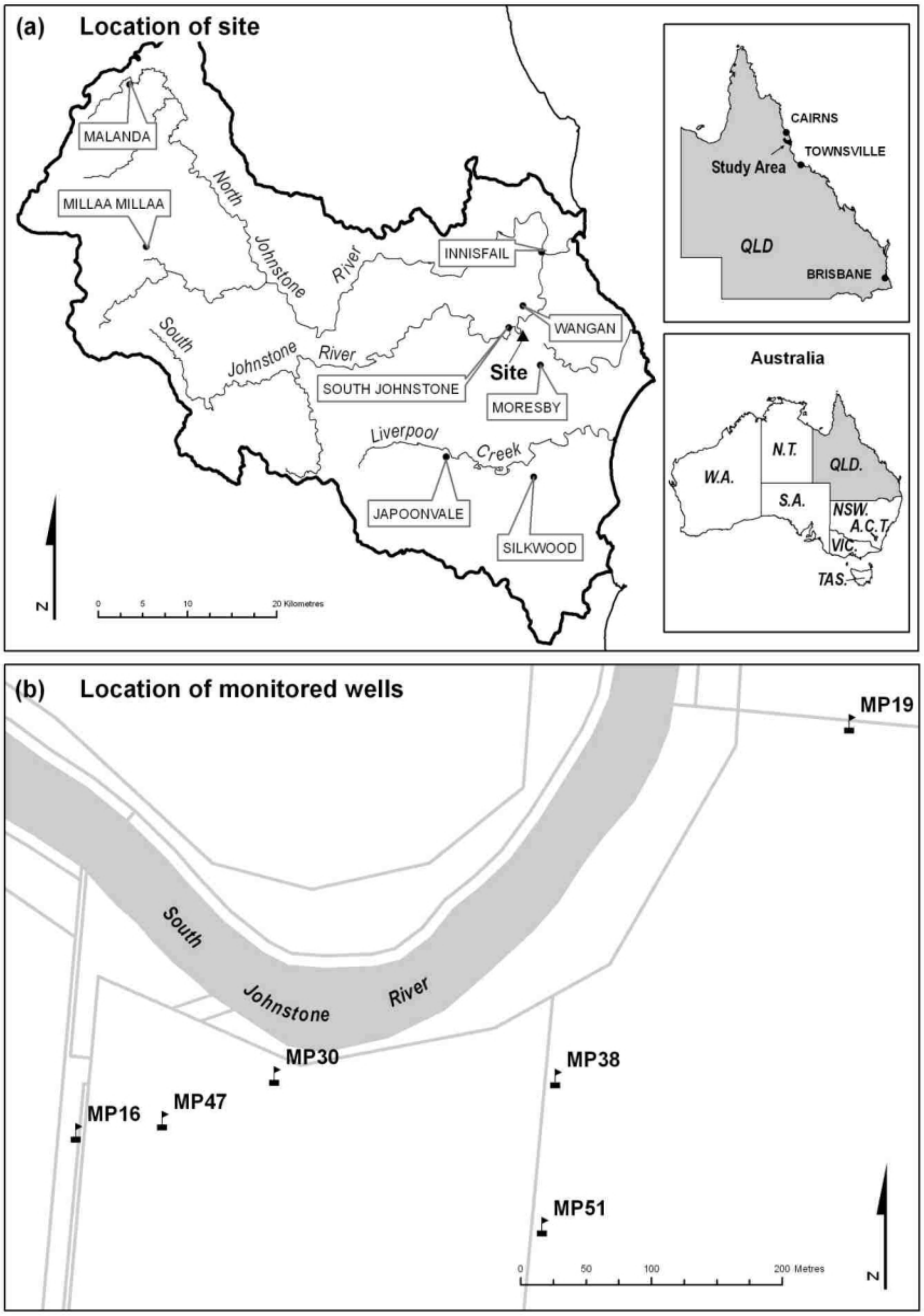

Figure 1. The Johnstone River Catchment (a) and the distribution of the wells in the farm in relation to the South Johnstone River (b). QLD refers to Queensland State in Australia where the study was conducted. MP16, MP19, MP30, MP38, MP47, and MP51 are the wells monitored in the farm.

can lead to complex subsurface flow paths, but this aspect has received little attention in the past. The GW flow is assumed to follow the undulating topography and surface drainage features. The major soil types in the cultivated areas belong to the Ferrosol soil order (Isbell, 1994). This is usually red to brown, acidic, well-structured with high clay content (20-70%) formed on basalt and also includes the Pin Gin series formed on alluvium derived from basalt. The saturated hydraulic conductivity in the top 0-0.1 m is relatively high, ranging from 5.1 to 17.1 m d^{-1}, and 0.14 to 0.27 m d^{-1} between 0.5 and 1.0 m (Bonell et al. 1983).

Rainfall

The summer rainy season (January through to May) in the region is characterized by an average rainfall of 2350 mm (60-yr average) and downpours as high as 200 mm d^{-1} are common (Hair, 1990). The cumulative percolation during the rainy season could be greater than 700 mm yr^{-1} (Hair, 1990).

Piezometer wells

The piezometers (simply the 'wells') used in this study were installed in early 1991 for GW monitoring and extraction feasibility studies, consequently the well design arrangement was beyond our control. Nevertheless, we selected these wells to study nitrate leaching to GW as there is an urgent need for this information to resolve its export from GW, under intensively cultivated sections of agricultural catchments, to streams and subsequent loading to the UN listed World Heritage GBR. The wells were located approximately 66 to 180 m away from the South Johnstone River bank (Figure 1b and Table 1). Although the wells were preexisting, below we provide a brief description of their installation for clarity.

Soil boreholes (96 mm diameter), ranging from 16 to 51 m deep, were drilled using a hydraulic rig. After coring, PVC pipes (43 mm internal diameter) with tightly sealed bases were inserted into the boreholes and grouted to serve as piezometer wells (Table 1). Prior to insertion a segment of each pipe was slotted and wrapped with 250 µm seamless polyester filter socks to facilitate water inflow into the wells but prevent coarse sand particles from entering the wells. The slotted segments ranged from 3 to 33 m (Table 1). The space between the pipes and bore-walls was backfilled tightly with coarse sand-gravel mix up to the slotted segment, measured from the sealed base of each pipe. A bentonite collar was placed just above the slotted segment of each pipe, measured from soil surface, to prevent water entry from above the collar. The remaining spaces between the bore-wall and the pipes were tightly backfilled with grout and soil-gravel material, exclusive of the top 0-0.5 m depth which was filled with cement. Approximately 1 m of the pipe

Table 1. Geophysical characterization of the wells.

Wells						
	<…………..Group-I wells…………………..>			<…………Group-II wells……………….>		
Characteristics	Shallow well (MP16)	Medium deep well (MP30)	Deep well (MP47)	Shallow well (MP19)	Medium deep well(MP38)	Deep well (MP51)
	(…………………………………...m………………………………………………………..)					
Well depth	16	30	47	19	38	51
Well elevation	10.57	12.36	10.90	13.49	14.28	13.81
Distance from the river	150	66	145	140	110	180
Slotted depth	13-16	18-30	11-47	13-19	20-38	18-51
Regolith stratigraphy						
Soil material	Between at depths (m)					
Clay	0-12	0-14	0-11	0-14	0-11	0-9
Silty-clay	12-14	14-16	-	14-16	11-21	9-16
Coarse sand plus gravel	14-16	16-30	11-30	16-19	21-30	16-32
Heavy silty-clay	-	-	42-47	-	30-38	32-51
Basalt	Fragments (at > 16 m depth)	Schist (at > 30 m depth)	Schist (at > 47 m depth)	Fresh hard (at > 19 m depth)	Fresh, small (at > 38 m depth)	Rock/schist (at > 51 m)
Distance between wells (m)						
	<………..162………………..>			<………...348……………..….>		
		<……….94……………>			<……..……115……..>	
	<…………………67………………………..>			<……………..450…………………………>		

was above the soil surface and top end was covered with a lockable cap. The water table levels reported in the text are depths to GW from soil surface.

Groundwater and hydrochemical monitoring

Depth to water table measurements and water sampling for solute analysis were conducted at 7-10 day intervals from January through to May (rainy season) commencing in 2003 and ending in 2005. Monitoring and sampling were scheduled to occur 12-24 hr after major rainfall events, and after dry-spells that lasted for at least 2- 3 days. The former provided information on the rising GW and the latter on the receding water. The depth to water table was measured using a special tape with a noise trigger device and water samples were collected following the procedures described by Alexander (2000) for solute determinations. The samples were kept at approximately 4^{o}C in the field and upon arrival in the laboratories were analyzed for nitrate-N, chloride, and EC using the procedure described by Rayment and Higginson (1992). The daily rainfall during the investigation period was recorded at the research station located at less than 1 km away from the monitoring site (Table 2).

Table 2. Monthly rainfall distribution during the investigation compared with the 80 year average values.

Year	The monthly rainfall distribution during the rainy season							
	December	January	February	March	April	May	June	Total
	(……………………………….mm month^{-1} ……………………) mm							
2003	461	17	146	265	497	289	147	1822
2004	357	329	597	944	528	152	99	3006
2005	143	463	98	573	517	74	168	2036
CV(%)	45	67	7845	45	12	521	21	25
60-yr average	259	514	567	607	399	266	157	2769

Cropping and fertilizer history

The site was under native rainforest before being deforested for cultivation in the early 1950's and it has been under intensive crop production systems until now. Before the mid 1980's a trash-burn (burning all trash after harvest) sugarcane production system was in operation, this changed to a green-blanket (leaving all trash on the ground after harvest) until 1990 and then changed to the current banana production. The fertiliser-N input for the banana during the study period ranged from 310 to 525 kg N ha^{-1} yr^{-1} as urea and/or diammonium phosphate. The fertiliser was split applied (8 to 20 annual applications and it was fertigated during the dry months (July to mid-December).

Flow velocity and solute mass flux computations

Flux theory (Fetter, 1999) was used to clarify the issue of lateral transport of solutes. The lateral flow gradient (LHG) between 2 wells was defined as:

$$LHG = (H_1-H_2)/l \tag{1}$$

In Equation (1) H_1 and H_2 were hydraulic heads in 2 wells, where $H_1 > H_2$, and l was the shortest distance between wells (Fetter, 1999).

Lateral flow velocity (V_l) via pore space across unit cross-sectional area of soil matrix was defined as follows;

$$V_l = (Ks/\eta) * (dh/dl) \qquad (2)$$

where *Ks* was saturated hydraulic conductivity and *dh/dl* hydraulic gradient, which in our study was defined by Equation (1). The η was effective porosity which we assumed as 0.15 (Rasiah et al. 2003) and subsurface *Ks* in Equation (2) as 0.72 m d^{-1} (Australian Soil Resource Information (ASRI) 2001; Rasiah et al. 2011a; and unpublished pump test data). The use of *Ks* = 0.72 m d^{-1} had been a contentious issue considering that is can vary substantially down to 51 m depth (See Bonell et al. 1983). The unpublished pump test data available only for 10 m deep wells in an alluvial regolith in the nearby catchment produced *Ks* = 0.72 m d^{-1}. The ASRI indicates that *Ks* could range from 0.72 to 7.2 m d^{-1} for the basaltic regolith. The sensitivity analysis for *Ks* using the unpublished pump test data (0.72 m d^{-1}) for the alluvial aquifer indicated even this was not satisfactory to characterize the rapid fluctuations in water tables. (Rasiah et al. 2011a). Even though the well depths ranged from 16 to 51 m the lateral- flow occurred from at depth < 15 m regardless of the well depth (more details in the results section). This suggested one single *Ks* is sufficient to characterize lateral-flow at < 15 m depth. Thus, for consistency, based on ASRI and pump test data, we chose *Ks* as 0.72 m d^{-1} in this study also.

The advective mass flux of solutes (F_l) in one dimensional flow was defined as a function of its concentration and the amount of water that flowed across unit cross-sectional area as follows (Fetter, 1999),

$$F_l = V_l \eta C \qquad (3)$$

where C is the concentration of a given solute.

Statistical analysis

The descriptive statistical parameters mean, standard error, median, minimum and maximum, and the coefficient of variation (CV) were computed to statistically characterize the temporal behavior of water table, hydraulic- and pressure- heads and solute concentrations across three rainy seasons (von Asmuth and Knotters, 2004). Simple linear correlations were performed to determine the type of association between two variables. The SAS (1991) software package was used for the aforementioned analysis.

RESULTS AND DISCUSSION

Regolith stratigraphy

The data shown in Table 1 show the top 9-11 m of the regolith was generally clayey and underneath this was a silty-clay layer that ranged in thickness from 2 to 10 m. Underneath the silty-clay layer was coarse sand-gravel mix material which ranged in thickness from 11 to 32 m. A heavy silty-clay layer that ranged in thickness from 5 to 19 m was found underneath the coarse sand-gravel mix material. It is apparent that the 51 m deep regolith was stratified and the stratification shows the porous coarse sand-gravel mix material was being sandwiched between clay-silt layers. We define the top 20 m thick clay-silt material as RL1, the sand-gravel mix as RL2 and the third heavy silty-clay as RL3. Based on the aforementioned regolith stratigraphy and our experience we define the aquifer segment < 20 m deep as shallow (SW), 0 to 38 m as medium deep (MW), and 0 to 51 m as deep (DW).

The regolith stratigraphy in conjunction with the slotted lengths (Table 1) in the pipes indicated the SW intercepted waters between 13-19 m depth, i.e. from 6 m thick regolith material. Between 13-19 m there was a 2 m thick clay layer, 2 m thick silt-clay, and 2-3 m thick sand-gravel mix. The MW intercepted waters at 18-38 m depth, i.e. from 20 m thick regolith material. Between 18-38 m depth there was a 9-14 m thick coarse sand-gravel mix material and 8 m thick heavy silty-clay material. The DW intercepted waters from 14-16 m thick coarse sand-gravel mix layer and from 5-19 m thick heavy silty-clay material. Overall, the SW intercepted waters from 3-6 m thick regolith material compared with 12-18 m for the MW and 33-36 m for the DW. In general, it seems the SW wells intercepted the major proportion of waters from clay-silt material compared with coarse sand-gravel mix for MW and heavy silty-clay plus coarse sand-gravel mix for DW.

From the foregoing regolith and water interception characteristics, the proximity of the wells to each other, and for simplicity we arranged the six wells in two groups. The shallow well MP16, the medium deep MP30, and the deep well MP47 in one group (group-I) and the other three well (MP19, MP38, and MP51) in group-II (Figure 1b). These groupings may also be considered as pseudo-replicates.

Rainfall

The monthly rainfall distribution during the investigation period, mid-December through to mid-May, in a given year varied substantially during and between the rainy seasons and the large monthly variations are supported by CVs as high as 78% (Table 2). Compared with the 80 year long-term average, the 2004 rainy season was relatively wet; whereas the 2003 and 2005 seasons were dry (2003 was the driest, by about 1100 mm). The long-term distributions generally agreed with that of 2004, while the 2003 and 2005 showed substantial deviations. The variation in rainfall across the 3 rainy seasons for a given month was substantial and this is supported, again, by high CVs (12% to 78%). The largest monthly variation during the study period was observed for February, followed by January, May, March, and June, respectively.

Temporal behavior of groundwater

The data shown in Figure 2 indicate the depths to GW, measured from the soil surface, and the hydraulic heads (HH) changed temporally within and between rainy seasons in the 6 wells. The water tables rose and receded repeatedly during a given rainy season, suggesting the GW down to 51 m depth was dynamic and contiguous. The regression between rainfall (RF) and HH indicates only 27% to 38% of the changes in HH was accounted for by RF, implying the major proportion of the changes in HH were controlled by other unknown factors (Table 3). The slopes of the equations for the shallow wells (SW) are not significantly different from each other and similar trends were observed for medium deep (MW) and deep (DW) wells. This suggests the hydraulic responses of the wells, belonging to three hypothetical classes (SW, MW, and DW), to rainfall induced changes in HH were physically similar, and implying the well classification is satisfactory. A comparison of the slopes of the equations for the SW and MW in a group indicates the physical response to rainfall was significantly different from each other and a similar trend was observed for that between the MD and DW in a given group. This suggests the grouping of the wells is also satisfactory and these two groups could also be considered as pseudo-replicates. The regression equations provided mathematical support to the hypothesis that the hydraulic behavior of the three wells in a given group was significantly different from one another.

The CV's and the minimum and maximum for the HH (Table 4), obtained using the data pooled across the three seasons, indicate the temporal changes were largest in DW followed by MW, and

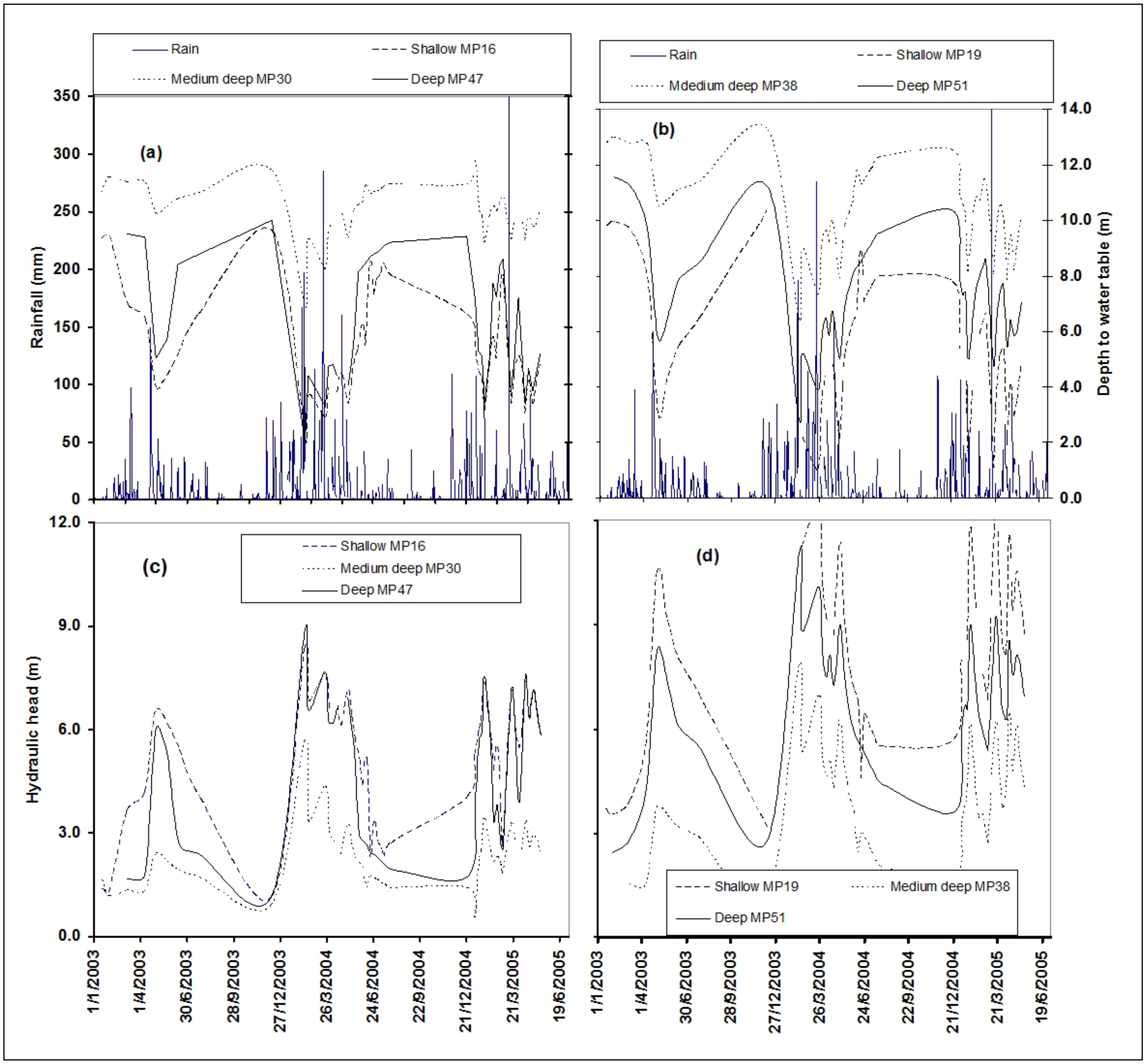

Figure 2. The impact of rainfall distribution on the temporal changes in (a, b) depth to groundwater and (c, b) hydraulic heads. Rainfall temporal distributions shown in (a).

SW, exclusive of DW-MP51. Intuitively the rapid changes were anticipated in the reverse order as the infiltrating rainwater to mix first with the 'old' GW at shallower depths first rather than at deeper depths (Love et al. 1993). Thus it seems changes were induced not only by the infiltrating rainwater but also by other variables such as the river-aquifer connectivity and the proximity of the wells to the river.

The river bed was about 10 m deep from the river bank and most of the slotted segments on the pipes were in parallel alignment with the river flow, except for in MW-MP38. In this well the slotted segment was well below the river bed. Only 2 m of the sand-gravel mix layer of the SW-MP16 and MW-MP30 of the group-I wells was in alignment with river flow compared with 9 m for DW-MP47. If the length of the slotted segments aligning with river flow had an impact on the temporal changes in GW then changes should have been highest in DW-MP47 and similar between SW-MP16 and MW-MP30. The changes in DW-MP47 are as anticipated but not those in SW-MP16 and MW-MP30 (Table 4). The changes in MW-MP30 were higher than SW-MP16 and this

Table 3. Simple linear correlation between hydraulic head and rainfall and that between solute flux and lateral hydraulic gradient.

Simple correlation between hydraulic head (HH) and the rainfall (RF) received between monitoring.	R^2
**HHMP16 = 5.10 + RF 4.21 x 10^{-3} (1.37 x 10^{-3})	0.38
**HHMP19 = 7.76 + RF 5.67 x 10^{-3} (1.56 x 10^{-3})	0.38
*HHMP30 = 2.19 + RF 1.80 x 10^{-3} (9.48 x 10^{-4})	0.30
*HHMP38 = 3.82 + RF 3.02 x 10^{-3} (1.50 x 10^{-3})	0.30
*HHMP 47 = 4.58 + RF 3.66 x 10^{-3} (1.10 x 10^{-3})	0.28
**HHMP51 = 6.32 + RF 4.62 x 10^{-3} (1.88 x 10^{-3})	0.37
Simple linear correlation between lateral solute fluxes and the corresponding lateral gradient (LHG)	
Group-I wells	
Ion flux MP16_MP30 = 23.98 (2.37) LHG MP16_MP30	0.76
Chloride flux MP16_MP30 = 4.41 (0.51) LHG MP16_MP30	0.70
Nitrate flux MP16_MP30 = 8.41 x 10^{-1} (6.11 x 10^{-2}) LHG MP16_MP30	0.84
Group-II wells	
Ion flux MP19_MP38 = 16.19 (0.83) LHG MP19_MP38	0.93
Chloride flux MP19_MP38 = 3.78 (0.22) LHG MP19_MP38	0.91
Nitrate flux MP19_MP38 = 5.18 x 10^{-1} (5.01 x 10^{-2}) LG MP19_MP38	0.80
†The correlations are significant at $P < 0.05$. MP16 and MP19 are shallow wells, MP30 and MP38 are medium deep wells, and MP47 and MP51 are deep wells. HH is hydraulic head, LHG is lateral hydraulic gradient, RF is rainfall, MP16_MP30 refers to the lateral gradient or solute flux the shallow well MP16 to the medium deep well MP30 and similarly for other wells. R^2 is coefficient of determination.	

can not be the differences in slotted segment alignment with the river. The MW-MP30 was the nearer to the river than SW-MP16 suggesting the more rapid changes in MW-MP30 than SW-MP16 could be due to the close proximity of the former than the latter to the river.

A similar analysis for the group-II indicates that 2-3 m thick slotted segment of SW-MP19 and DW-MP51 were in alignment with the river compared with zero for MW-MP38 which was characterized by the largest changes in HH. On the other hand MW-MP38 was nearer to the river than SW-MP19 or DW-MP51, which was the furthest away from the river and characterized by the smallest changes. It seems the well proximity to the river also played a role in controlling the temporal changes along with the well-river connectivity via the slotted segment. Thus in general it seems the temporal changes in HH down to 51 m are complex even within short separation distances among the wells. It seems that in this highly weathered regolith the temporal changes in GW were due to (i) rainfall amounts and distributions (ii) gaining GW via stream intrusion during rainfall events (iii) losing GW to streams during dry spells between rainfall events and (iv) both by variably gaining and losing situations depending on the rainfall distribution and the time of the year.

The temporal changes in GW down to 51 m depth indicate the rainwater (RF) mixed with 'old' GW down to 51 m via percolation and/or river intrusion i.e. a loosing river condition. The temporal changes in HH during the dry season, July to mid December, was very small (data not shown),

Table 4. Statistical characterization of hydraulic and pressure heads and depth to water table.

Hydraulic head						
	<………Group-I wells……………>			<………Group-II well ……………..>		
	Mean hydraulic head (m)					
Rainy season	Shallow well (MP16)	Medium deep well (MP30)	Deep well (MP47)	Shallow well (MP19)	Medium deep well (MP38)	Deep well (MP51)
2003	4.09±0.81	1.71±0.17	3.50±0.91	6.33±0.82	2.49±0.44	5.20±0.99
2004	5.52±0.52	2.65±0.31	5.00±0.61	8.32±0.70	4.51±0.43	7.29±0.51
2005	5.75±0.28	2.42±0.16	5.24±0.41	9.08±0.44	4.33±0.28	6.93±0.31
	Hydraulic heads (m) from the data pooled across the three seasons					
Mean	5.38±0.28	2.38±0.15	4.92±0.33	8.29±0.40	4.13±0.24	6.81±0.30
Minimum	1.14	0.58	1.19	3.16	1.01	2.44
Maximum	8.34	5.66	8.88	12.44	7.82	11.06
CV (%)	33	39	42	30	38	28
	Depth to water table (m) from soil surface from the data pooled across the three season					
Mean	5.54±0.52	10.19±0.19	6.72±0.64	5.71±0.67	10.64±0.35	7.88±0.51
Minimum	3.02	8.53	3.41	1.75	8.28	4.50
Maximum	8.68	11.47	9.97	9.36	12.93	10.49
	Pressure head (m)					
Mean	10.65±027	19.93±0.14	40.61±0.31	13.67±0.38	27.62±0.23	43.62±0.28

†CV is coefficient of variation

suggesting a gaining river situation at the expense of the GW. The rapid decreases between rainfall events during the rainy season are important in this region as it can contribute towards nutrient export to gaining streams (Rasiah et al. 2011a).

Regardless of the well depths, the maximum depth to water table from soil surface was < 13 m throughout the year, suggesting the lateral-flow occurred throughout the year from the top clayey layer of the regolith, i.e., from the shallow aquifer segment (Table 4). This provides further support to our claim that there is no need for different Ks for different regolith layers (See materials and methods) for the computation of flow velocities from different layers.

The mean hydraulic pressure heads indicate that lateral-flow would have occurred from the DW to MW and from the latter to SW (Table 4). The ground elevation on the other had indicates the flow was from the MW to DW and from the latter to SW (Table 1). The HH which integrate the impact of pressure head and elevation indicates the flow was from SW to DW and to MW and from DW to MW. The HH is the primary variable that will determine flow direction; therefore we will place our emphasis on this hydraulic parameter hereafter.

Lateral hydraulic gradients

The lateral hydraulic gradients (LHG) shown in Figure 3 indicate that GW water flowed laterally from the SW to MW and to DW. The flows gradients changed temporally as indicated by high CV's and the changes were higher than HH (Tables 4 and 5). A comparison of the mean LHG or the CV between a given well in a given group with the corresponding well in the other group indicates the flow behavior of the two groups was different (Table 5). Generally the temporal changes in LHG were higher in group-I wells than group-II. According to Mackie (2002) these two groups of wells can be considered as two hydrostructural domains which are in regolith materials with similar transmissive and storage properties, but their temporal behavior could be different. Park et al. (2008) suggested there could be several hydrostructural domains over short distances, but did not offer any reason(s) for the differences. De Vries and Simmers (2002) reported that despite numerous studies, experimental characterization of lateral-flow remains an uncertainty,

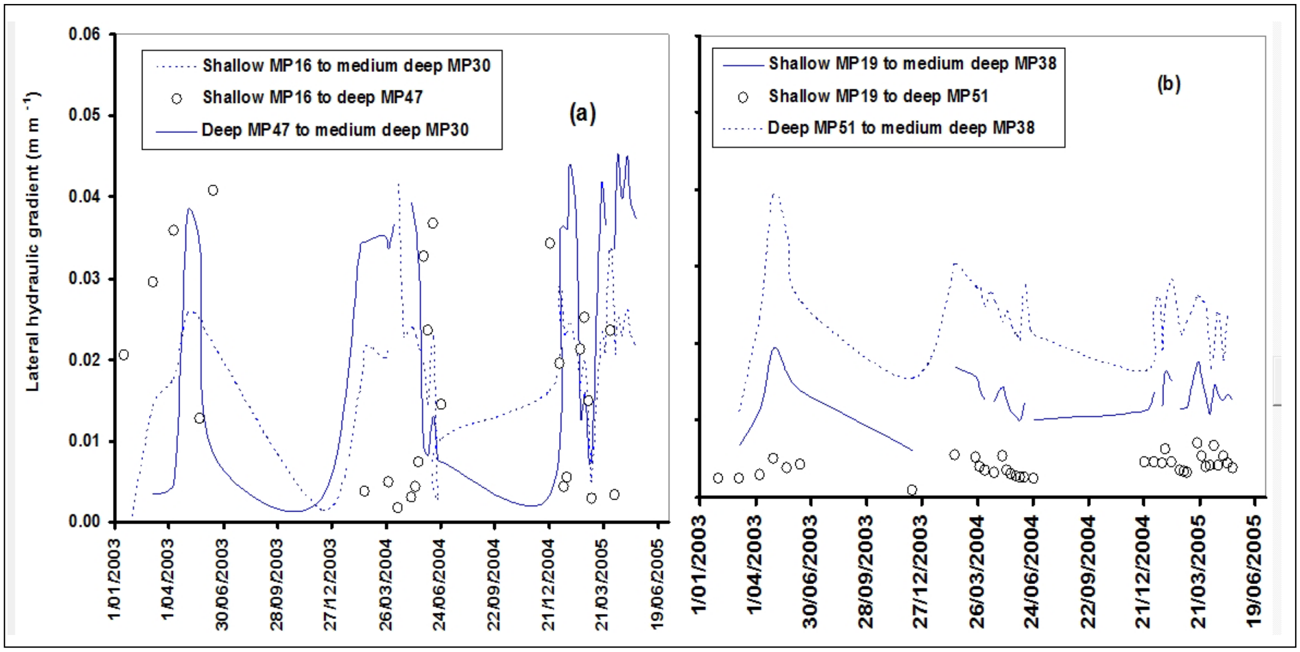

Figure 3. Temporal changes in lateral hydraulic gradients obtained using Equation (2).

particularly in situations where preferential flows occur. Thus, it seems the differences between the two domains (group-I and group-II wells) with regard to the temporal changes in flow gradients over short distances might have been due to differences in preferential flow. Preferential flow in this highly weathered regolith is a norm rather than an exception (Rasiah et al. 2011b).

Flow domains

The minimum and maximum depth to water tables indicates the flow from the SW occurred at depths between 2.39-9.02 m compared with 8.41-12.20 m for MW, and 3.96-10.23 m for DW (Table 4). It seems there was an overlap of flow domain among the wells belonging to different depth classes (Table 4). Furthermore, the maximum depths to water tables indicate that flow from

Table 5. A summary of the descriptive statistics for lateral hydraulic gradients and lateral solute fluxes.

	Lateral hydraulic gradients (m m $^{-1}$)					
	<……… Group-I wells……………………..>			<…………..…Group-II wells…………..>		
	From MP16 to MP30	From MP16 to MP47	From MP47 to MP30	From MP19 to MP38	From MP19 to MP51	From MP51 to MP38
Mean	1.98×10^{-2} ±$1.20 \times 10^{-3)}$	1.55×10^{-2} ±2.44×10^{-3}	2.63×10^{-2} ±2.45×10^{-3}	1.26×10^{-2} ±5.21×10^{-4}	4.05×10^{-3} ±2.18×10^{-4}	2.38×10^{-2} ±7.86×10^{-4}
Minimum Maximum	7.41×10^{-4} 4.16×10^{-2}	1.10×10^{-4} 4.07×10^{-2}	2.98×10^{-3} 4.62×10^{-2}	4.58×10^{-3} 1.94×10^{-2}	8.44×10^{-4} 6.96×10^{-3}	1.11×10^{-2} 3.92×10^{-2}
CV (%)	40	83	57	25	33	21
	Solute fluxes (g m $^{-2}$ d $^{-1}$)					
Ion	2.11×10^{-2} ±1.23×10^{-3}	4.23×10^{-1} ±8.41×10^{-2}	1.09×10^{0} ±1.40×10^{-1}	2.15×10^{-1} ±1.14×10^{-2}	7.00×10^{-2} ±4.06×10^{-3}	9.80×10^{-1} ±5.90×10^{-2}
Chloride	8.78×10^{-2} ±1.35×10^{-2}	6.12×10^{-2} ±1.94×10^{-2}	2.50×10^{-1} ±3.56×10^{-2}	4.99×10^{-2} ±3.20×10^{-3}	1.04×10^{-2} ±7.76×10^{-3}	5.82×10^{-2} ±2.89×10^{-3}
Nitrate	1.80×10^{-2} ±1.73×10^{-3}	2.19×10^{-2} ±5.82×10^{-3}	5.91×10^{-2} ±9.06×10^{-3}	6.83×10^{-3} ±6.92×10^{-4}	2.39×10^{-3} ±2.71×10^{-4}	3.17×10^{-3} ±9.48×10^{-4}

†CV is coefficient of variation. The numbers below the means are standard errors. MP16 and MP19 are shallow wells, MP30 and MP38 are medium deep wells, and MP47 and MP51 are deep wells.

different depth classes occurred from the top 9.02-12.20 m depth, implying the flow occurred only from the shallow aquifer segment (Figure 2 and Table 4). This suggests the quantification of the lateral-flow from the shallow aquifer segment is sufficient to account for total lateral discharge. In order to resolve this issue we undertook two approaches.

Firstly, the hydrograph analysis shows the flow from different aquifer segments were different (Figure 3). The area under a given curve (Figure 3) was the total flow from that aquifer segment and the difference between two curves was the difference in contribution between two aquifer segments. Secondly, a statistical approach was undertaken to further clarify the issue. In this approach we defined LHG as a function of hydraulic head (HH), depth to water table (WT), well elevation, pressure head, the number of regolith layers (RL) covered by a given well, and the interaction terms involving HH and RL and WT and RL. The stepwise multiple regression analysis produced the following empirical model:

$$LHG = 3.72 \times 10^{-2} - 4.72 \times 10^{-3} \quad WT + 1.03 \times 10^{-3} \quad RL * WT$$

$(R^2 = 0.62,\ P < 0.08)$

Although the model is significant at $P < 0.08$, we consider this level of significance is satisfactory for field data to explore the physical basis for flow differences. The RL in the above model was a qualitative variable in which RL was set to 1 when the aquifer segment covered only one regolith layer (RL = 1 (for the SW), RL = 2 (for MW), and RL = 3 (for DW). The above model indicates the lateral-flow increased with decreasing WT from ground surface. However, the interaction term involving RL and WT indicated a reverse trend for the influence of WT. This implies that at constant WT the LHG will increase with increasing number of RL, suggesting that when the river level rose it lost water to the aquifer or river intrusion occurred with increasing well depth. This illustrates the impact of RL on integrating the influence of regolith stratification on LHG. Therefore based on the hydrographs and the statistical model we claim the temporal changes in lateral-flow from the three aquifer segments are distinctly different from each other and the total flow is the sum from the three segments.

It has been usually assumed that localized flow occurs only from shallow aquifer segments and therefore estimating lateral flow from this segment is sufficient (Love et al. 1993; Bout et al. 2010). Our results are not consistent with the aforementioned findings. Furthermore, Love et al. (1993) reported that the major proportion of the regional flow from the Gambier Embayment aquifer in South Australia, from the upper segments of the unconfined aquifer was controlled by local ground elevation which is not consistent with our findings (see the above statistical model). Therefore we suggest that in humid tropical environments similar to ours the localized lateral-flow can occur even from moderately deep to deep aquifer segments.

Behavior of the solutes in groundwater

The behavior of solutes in GW shown in Figure 4 indicates the concentrations changed temporally with repeatedly increasing and decreasing trends during a given rainy season and between seasons. The rapid changes or variations are supported by high CVs, 28% to 61% (Table 6). For example, nitrate-N in the SW-MP16 varied from 50 to 4200 $\mu g\ L^{-1}$ during the 2003 season and similar trends were observed for Cl and EC and in the other wells. The solute dynamics when superimposed on that of GW (Figures 2 and 4) indicate the concentrations increased with rising GW and decreased when it receded regardless of well depths and results are consistent with those reported by the authors for the other humid tropical catchments in this region (Rasiah et al.

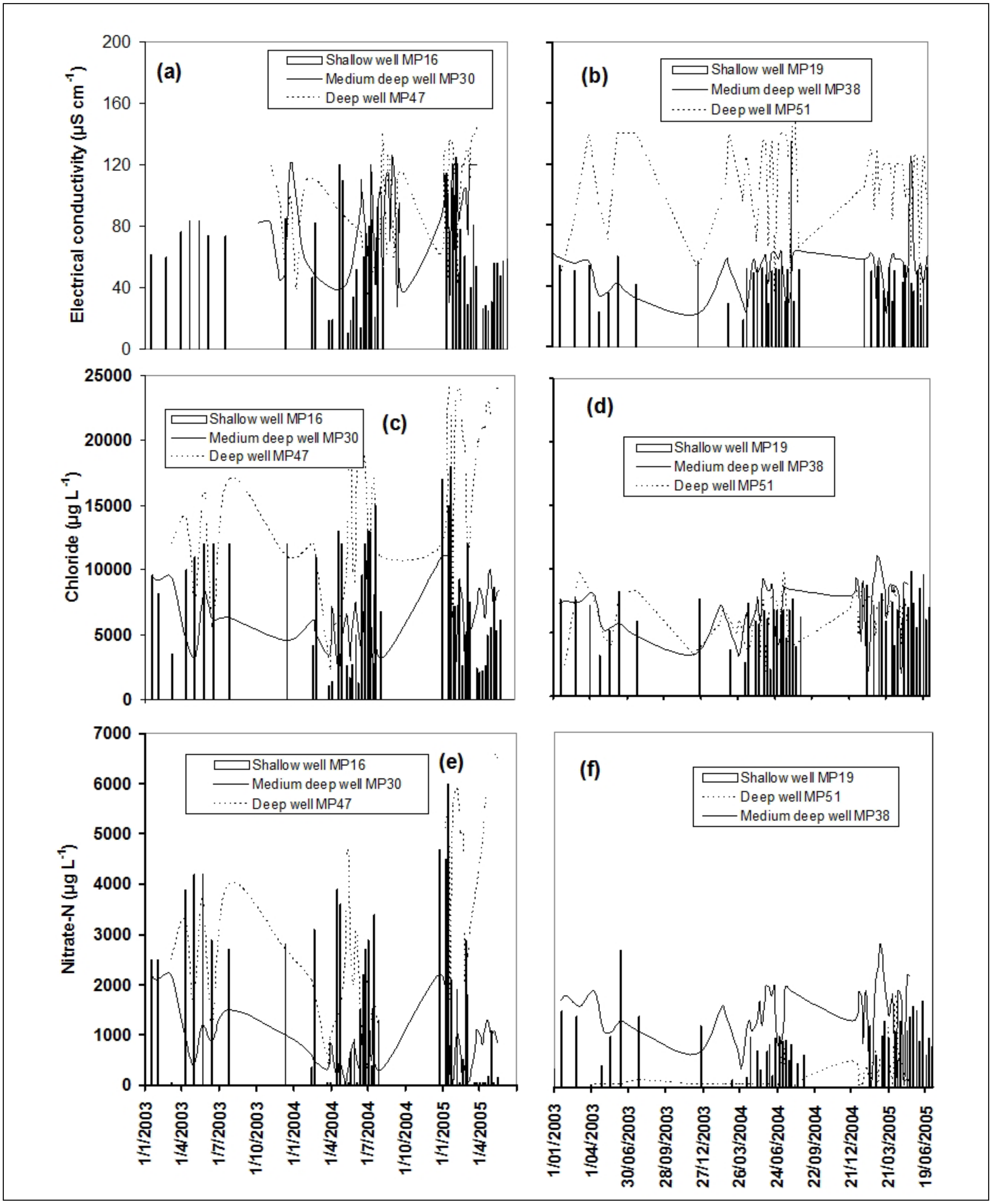

Figure 4. Temporal changes in solute concentrations in groundwater.

2011a,b; 2010). The simultaneous increasing and decreasing trends of the solutes and GW indicate the solutes were imported into the GW after rainfall events via rainwater infiltration and/or river intrusion and a reverse trend, exported out from GW to the river, when the GW receded. The decreases in concentrations were due to lateral transport in receding water and/or biogeochemical reactions in GW. The potential exists for adsorption/desorption reactions to occur down to 12 m depth in this soil (Rasiah et al. 2003b), but biological decomposition issue is unsolved for this region. The solute dynamics in conjunction with that of the GW indicates mixing of solutes, both 'old' and new, occurred down to 51 m depth.

If solute mixing occurred down to 51 m depth then intuitively one would anticipate the concentrations to be similar regardless of well depths. The mean nitrate concentrations indicate there were no significant relationship trends between solute concentration and well depth (Table 6). To further clarify the solute concentration issue with well depth, we chose the non-reactive Cl and found that there were significant differences between the concentration among group-I, but such trends were not apparent among group-II wells. Even in among group-I wells there wasn't a specific trend. Thus, we suggest solute mixing was random, presumably due to preferential flow of rainwater and/or the gaining/loosing river condition. Unlike the hydraulic stratification induced that by the regolith, solute gradients with depth were not apparent and this suggests that regolith dissolution/adsorption reactions contributing towards solute gradients in GW was small to negligible. This indirectly suggests the solutes in GW were sourced primarily from surface applied fertilizers and organic matter decomposition.

Lateral transport of solutes

The solute mass fluxes computed using the data shown in Figures 3 and 4 in Equation (3) and shown in Figure 5 indicate the fluxes changed temporally, similar to that observed for lateral gradients. The mean mass fluxes were highest from the DW, followed by the SW and MW, respectively, but with few exceptions (Table 5). The fluxes generally followed the flow gradients suggesting advective transport of solutes in lateral-flow (Figure 5). The advective transport mechanism is supported by the empirical regression models listed in Table 3. These models indicate that 70 to 93% of the variability in solute fluxes was controlled by flow gradients. The larger control exerted by the flow gradients of group-II wells than group-I wells can not be attributed to higher flow gradient of the former as it was less than the group-I wells. The differences can not also be attributed to differences in fertiliser inputs, as it was uniform across the farm.

Hereafter, our emphasis will be on nitrate flux, because of the concern raised with regard to its loading in sensitive aquatic ecosystems in northeast humid tropic of Australia (Baker 2003). The

Table 6. A summary of the descriptive statistics for the solutes in groundwater.

Solute concentrations						
	<…………...Group-I wells…………..>			<…… Group-II wells……………..>		
	Shallow well (MP16)	Medium deep well (MP30)	Deep well (MP47)	Shallow well (MP19)	Medium deep well (MP38)	Deep well (MP51)
	Nitrate (μg L^{-1})					
Mean	1912±421	978±158	1990±239	951±156	1429±141	190±53
Median	1297	918	2833	1010	1517	157
CV (%)	33	61	52	54	39	34
	Chloride (μg L^{-1})					
Mean	8053±944	6755±638	13635±1485	6357±497	6709±500	6331±598
Median	7200	6953	14183	6733	7167	6783
CV (%)	56	35	40	28	29	34
	Electrical conductivity (μS cm^{-1})					
Mean	63±6	87±7	94±9	46±4	50±4	104±10
Median	61	84	99	49	54	114
CV (%)	43	32	34	34	31	36

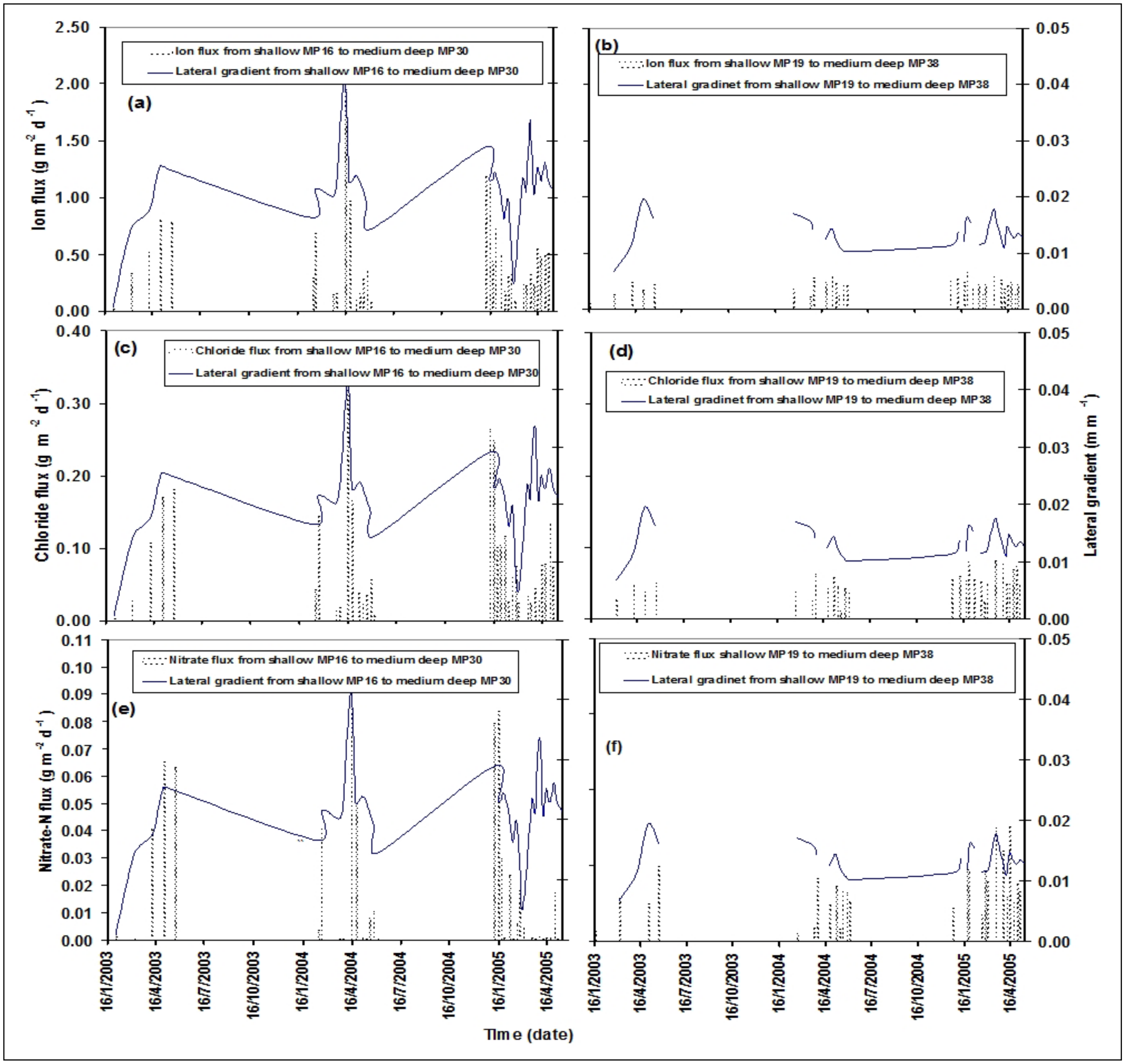

Figure 5. Temporal changes in solute fluxes obtained using Equation (3).

mean nitrate flux from the group-I wells was 9.90 x 10^{-2} g m^{-2} d^{-1} compared with 1.2 x 10^{-2} g m^{-2} d^{-1} for group-II. Compared with the about 8 fold differences in nitrate flux between the two groups of wells, that associated with the flow gradients was small (34% more for group-I wells than group-II). In the previous paragraph we indicated the control exerted by flow gradient on solute flux was higher in group-II wells than group-I. This contradiction suggests other variables also played a role in nitrate flux. The most obvious was the concentration differences between the two groups. The mean nitrate-N concentration (1627 μg L^{-1}) was higher in group-I wells than group-II (857 μg L^{-1}), suggesting that solute concentration also played a role in solute flux along with flow gradient. The differences in nitrate concentration between the two groups can not be attributed to differences in input and the reason for the spatial differences GW nitrate is unclear. However, the differences could be attributed to differences in preferential flow and the degree of river-aquifer connectivity as determined by the proximity of the wells to the river.

Nitrate fluxes in lateral-flow suggest there may be hazard associated with the presence and transport of it in the humid tropics, particularly in northeast Queensland, Australia. The presence of it in GW in relation to drinking water quality seems to be of least concern as the mean nitrate-N (1.0 to 1.3 mg L^{-1}) concentration in the SW was approximately one-tenth of the maximum permissible level (Table 6). On the other hand the concentrations are an order magnitude higher than the trigger values reported for most of the aquatic ecosystems health, including the UN listed World Heritage Great Barrier Reef (ANZECC, 2000). However, the concentrations in the GW can not be directly linked to ecosystem health as the risk depends on the quantities exported and proportional contribution that it makes toward the total loadings via runoff plus lateral-flow. The proportional contribution issue remains unresolved until now, but this study and other studies (Rasiah et al. 2011a, b; 2010; 2003a) have shown there was lateral transport to streams, suggesting the presence of nitrate in GW is an aquatic ecosystem health hazard in humid tropical agricultural catchments in general and in particular in this region. The quantities exported to streams will depend on the travel time and the biogeochemical reactions that nitrate may undergo during transport from the aquifer to streams. The travel time issue has been addressed partially by Rasiah et al. (2011a, 2012) for an alluvial aquifer in this region. They showed the estimates obtained using the Ks from pump test data were 2-3 times higher than those obtained using the water table recession data, thereby creating an uncertainty in the appropriateness of pump test Ks for situations where preferential flow is a major flow pathway. Intuitively the preferential flow is thought to be higher in the basaltic highly weathered than the clayey alluvial regolith, suggesting the need for further clarification in travel time estimates for this regolith.

The extraction of waters from aquifers and rivers for irrigation, mostly for banana production, during the dry season (June through mid December) is a contentious issue in this region. Although the regulations are in place to limit river water extraction but that with regard to GW is not explicitly clear. This study shows that GW and the river are connected or interact with each other up to at least 200 m away from the river. Further studies are required to assess the river-GW interaction at distances > 200 m. The river-GW connectivity of wells ranging in depth from 16 to 51 m and extending up to 200 m away from the river suggests that GW can be extracted from SW without much need for extraction from deep wells. This is attributed to the high hydraulic pressure head (Table 4) of the DW that can maintain continuous flow into SW thereby minimizing the need for extraction from DW. Even though GW extraction may have some impact on environmental flow requirement during the dry seasons, the extraction may help in reducing the nitrate levels in the river (gaining river) and also the beneficial utilization of nitrate for crop production via irrigation.

The nitrate in GW during last 10 years indicate there were no significant increasing or decreasing trends over this period (Personal observations) even though increasing and decreasing trends that were observed during rainy seasons (Rasiah et al. 2011a,b; 2010; 2003a). The long term stability despite substantial reduction in N-fertiliser inputs during the last decade suggests that nitrate export and/or biogeochemical reactions were responsible for maintaining stable nitrate levels in GW in this region.

CONCLUSIONS

The temporally changed, repeatedly increasing and decreasing trends, solute concentrations in space that followed the rising and receding groundwater (GW) levels, respectively, during rainy seasons indicated the aquifer in the top 51 m of the highly weathered regolith is hydraulically dynamic down to 51 m depth. The percolating rainwater (RF), GW, and the river water (RW) interacted and mixed with each other down to 51 m depth. The solutes mostly derived from the applied fertilizers in these waters followed the mixing behavior of the RF-GW-RW. The solutes, particularly nitrate was transported into the GW by the percolating RF and the rising RW during rainfall events and exported to the river between the events. The aquifer in the top 51 m of the regolith was contiguous but there were three hydraulically heterogenous segments and the heterogeneity was induced by regolith stratification. The lateral mass transport from different aquifer segments were different and the transport depended on the magnitude of the lateral flow gradient of a given aquifer segments and the nitrate concentration in the segment. Even though the lateral flow and the solute advective transport occurred independently and simultaneously from each aquifer segment, the flow domain of the three segments was in the top regolith layer.

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REFERENCES

Alexander, D.G. 2000. Hydrographic procedure for water quality sampling, Water Monitoring Group, Water Resource Information and Systems Management, Department of Natural Resources, Brisbane, Australia.

ANZECC. 2000. Australian water quality guidelines for fresh and marine waters. Australian and New Zealand Environment Conservation Council, Canberra, Australia.

Australian Soil Resource Information. 2001. http://www.anra.gov.au/topics/soils/pubs/national/agriculture_asris_shc.html.

Baker, J. 2003. A report on the study of Land-sourced Pollutants and their impact on Water Quality in and Adjacent to the Great Barrier Reef. Department of Primary Industries, Brisbane, Australia.

Bonell, M., D.A. Gilmour, and D.S. Cassell. 1983. A preliminary survey of the hydraulic properties of the rainforest soils in the tropical North-East Queensland and their implications for the runoff process. Catena*,* Vol. 4, pp. 57-78.

Boutt, D.F., P. Diggins, and S. Mabee, S. 2010. A field study (Massachusetts, USA) of the factors controlling the depth of groundwater flow systems in crystalline fractured-rock terrain. Hydrogeology Journal, Vol.18, pp. 1939-1954.

Carpenter, S.R., N.F. Caraco, and V.H. Smith. 1998. Non-point pollution of surface waters with phosphorus and nitrogen. Ecological Applications, Vol.8. pp. 559-568.

Conger, R.W. 1996. Borehole geophysical logging for water-resources investigations in Pennsylvania: U.S. Geological Survey Fact Sheet 218-95, pp.4p.

Cook, P.G., A.L. Herczeg, and K.L. McEwan. 2001. Groundwater recharge and stream baseflow: Atherton Tablelands, Queensland. CSIRO Land and Water. Technical Report 08/01, April 2001. Canberra, Australia.

De Vries, J. J. and I. Simmers. 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal, Vol. 10(1), pp. 5-17.

Fetter, C.W. 1999. Applied Hydrogeology (Second Edition). Merrill Publishing Company, A bell & Howell Information Company. Columbus, Toronto, London, Melbourne.

Hair, I.D. 1990. Hydrogeology of the Russell and Johnstone Rivers Alluvial valleys, North Queensland. ISBN 1034 7399, Department of Resource Industries, Brisbane, Australia.

Harte, P.T. 1997. Preliminary assessment of the lithologic and hydraulic properties of the glacial drift and shallow bedrock in the Mirror Lake area, Grafton County, New Hampshire: U.S. Geological Survey Open File Report 96-654A, 56 p.

Hunter, H., M. Sologinkin, S. J. Choy, A.R. Hooper, W.S. Allen, M.A. Raymond, and J. Peters. 2001. Water Management in the Johnstone Basin. NHT Project No 952194. Department of Natural Resources & Mines, Brisbane, Australia.

Isbell, R. F. 1994. Krasnozems. – 'a profile'. Australian J. Soil Research, Vol. 32, pp. 915-929.

Johnson, C.D. 2008. Effects of Lithology and Fracture Characteristics on Hydraulic Properties in Crystalline

Rock: Mirror Lake Research Site, Grafton County, U.S. Geological Survey, Pembroke, New Hampshire.

Keys,W.S. 1988. Borehole geophysics applied to groundwater investigations: U.S. Geological. Survey Open-File Report 87-539, pp. 305.

Keys, W.S., and L.M. MacCary. 1971. Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E1, pp.124.

Larkum,A.W.D., andA.D.L. Steven. 1994. ENCORE: the effects of elevated nutrient enrichment on coral reefs. 1. Experimental design and research programme. Marine Pollution Bulletin*,* Vol. 29, pp.112-120.

Leach, L.M.. 1986. Groundwater resources of the Atherton basalts, Atherton shire. Queensland Water Resources Commission, Mareeba regional Office, Australia.

Love, A.J., A.L. Herczeg, D. Armstrong, F. Stadler, and E. Mazor. 1993. Groundwater flow regime within the Gambier Embayment of the Otawy Basin,Australia: evidence from hydraulic and hydrochemistry. Journal of Hydrology, Vol.143, pp. 297-338.

Mackie, D. 2002. An integrated structural and hydrogeologic investigation of fracture systems in the upper Createaceous Nanaimo group, southern Gulf Islands. MSc Thesis, Simon Fraser University, Canada.

Park, Y.J., F. Cornation, S. Normani, J. Sykes, and E. Sudicky. 2008. Use of groundwater lifetime expectancy for the performance assessment of a deep geologic radioactive repository: 2. application to Canadian Shield environment. Water Resources Research, Vol 44(4): doi10.1029/2007WR006.

Prove, B.G., and P.W. Moody. 1997. Final Report on 'Nutrient Balances and Transport from Agricultural and Rainforest Lands'. Department of Natural Resources, South Johnstone, Qld., Australia.

Rasiah,V., J.D.Armour, and P.N. Nelson. 2011a. Identifying the major variables controlling the transport of water and analytes from and alluvial aquifer to streams. Journal of Environmental Hydrology, Vol.19, paper 110.

Rasiah,V., P.W. Moody, and J.D.Armour. 2011b. Soluble phosphate in fluctuating groundwater under cropping in the north-eastern wet tropics of Australia. Australian J Soil Research, Vol. 49, pp. 329-342.

Rasiah, V., J.D. Armour, A.L. Cogle, and S.K. Florentine, S. K.2010. Nitrate import-export dynamics in groundwater interacting with surface-water in a wet-tropical environment. Australian J Soil Research, Vol. 48, pp. 361-370.

Rasiah,V., J.D. Armour, T. Yamamoto, S. Mahendrarajah, and H.D. Heiner. 2003a. Nitrate dynamics in shallow groundwater and the potential for transport to off-site water bodies. WaterAir and Soil Pollution,Vol. 147, pp. 183-202.

Rasiah,V., J.D.Armour, N.W. Menzies, H.D. Heiner, M.J. Donn, and S. Mahendrarajah. 2003b. Nitrate retention under sugarcane in wet tropical Queensland deep profiles.Australian J Soil Research,Vol. 41, pp. 1145-1161.

Rayment, G.R. and F.R. Higginson. 1992. In Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Sydney, Australia.

SAS., 1991. SAS/STAT Procedure Guide for Personal Computers', Version 5. Statistical Analysis Systems Institute Inc. Cary, NC.

Selman, M. and S. Greenhalgh. 2007. Eutrophication: An Overview of Status, Trends, Policies, and Strategies. WRI Policy Note, 3, World Resources Institute. ISBN-978-1-56973-732-3.

UNEP. 1989. Coastal and marine environmental problems of the United Republic of Tanzania. UNEP Regional Seas reports and studies. No. 106.

VonAsmuth, J. R. and M. Knotters. 2004. Characterising groundwater dynamics based on a system identification approach. Journal of Hydrology, Vol. 296, pp. 118-134.

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